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Research article

THE EFFECT OF CYCLING CADENCE ON SUBSEQUENT 10KM RUNNING PERFORMANCE IN WELL-TRAINED TRIATHLETES

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ABSTRACT
The aim of this study was to examine the effects of different pedalling cadences on the performance of a subsequent 10km treadmill run. Eight male triathletes (age 38.9 ± 15.4 years, body mass 72.2 ± 5.2 kg, and stature 176 ± 6 cm; mean ± SD) completed a maximal cycling test, one isolated run (10km), and then three randomly ordered cycle-run sessions (65 minutes cycling + 10km run). During the cycling bout of the cycle-run sessions, subjects cycled at an intensity corresponding to 70% P_{max} while maintaining one of three cadences, corresponding to preferred cadence (PC), PC+15% (fast cadence) and PC-15% (slow cadence). Slow, preferred and fast cadences were 71.8 ± 3.0, 84.5 ± 3.6, and 97.3 ± 4.3 rpm, respectively (mean ± SD). Physiological variables measured during the cycle-run and isolated run sessions were VO_2, V_E, RER, HR, RPE, and blood lactate. Biomechanical variables measured during the cycle-run and isolated run sessions were running velocity, stride length, stride frequency, and hip and knee angles at foot-strike and toe-off. Running performance times were also recorded. A significant effect of prior cycling exercise was found on 10km running time ($p = 0.001$) without any cadence effect ($p = 0.801$, $\omega^2 = 0.006$) (49:58 ± 8:20, 49:09 ± 8:26, 49:28 ± 8:09, and 44:45 ± 6:27 $min \cdot s^{-1}$ for the slow, preferred, fast, and isolated run conditions, respectively; mean ± SD). However, during the first 500 m of the run, running velocity was significantly higher after cycling at the preferred and fast cadences than after the slow cadence ($p < 0.05$). Furthermore, the slow cadence condition was associated with a significantly lower HR ($p = 0.012$) and V_E ($p = 0.026$) during cycling than in the fast cadence condition. The results confirm the deterioration in running performance completed after the cycling event compared with the isolated run. However, no significant effect of cycling cadence on running performance was observed within the cadence ranges usually used by triathletes.

KEY WORDS: Bicycling, running, physiology, humans, biomechanics.

INTRODUCTION

The sport of triathlon comprises a sequential swim, cycle, and run over a variety of distances (Table 1). Of these, the 1.5km swim, 40km cycle, 10km run Olympic distance triathlon made its debut at the Sydney 2000 Olympics (Millet and Vleck, 2000). Numerous studies have investigated the effects of the cycle-run transition on subsequent running adaptation in triathletes (Bernard et al., 2003; Hue et al., 1998; Millet and Vleck, 2000). Compared with an isolated run, the first few minutes of triathlon

Table 1. Triathlon race distances (km). Taken from Millet and Vleck (2000)

Distance	Swim	Bike	Run
Long	3.8	180	42
Middle	2.5	80	20
Triathlon/ Olympic/ Classic/ Short	1.5	40	10
Sprint	0.75	20	5

running have been reported to induce increases in oxygen uptake (VO_2) (Bernard et al., 2003; Hue et al., 1998; Millet and Vleck, 2000; Vercruyssen et al., 2002), alterations in ventilatory efficiency (V_E) (Bernard et al., 2003; Hue et al., 1998; Millet and Vleck, 2000; Vercruyssen et al., 2002), and changes in muscle blood flow (Millet and Vleck, 2000; Bernard et al., 2003). The increase in energy cost varies from 1.6% to 11.6% (Millet and Vleck, 2000) and is a reflection of triathlete ability level, with superior triathletes performing more economically (Miura et al., 1999). These physiological changes may be related to cycling induced glycogen depletion, thermoregulation and dehydration (Hausswirth and Lehénaff, 2001; Hue et al., 1998; Lepers et al., 2001a; Millet and Vleck, 2000), or to alterations in biomechanical variables such as stride length (Gottschall and Palmer, 2002; Hue et al., 1998; Vercruyssen et al., 2002).

It appears that minimising energy expenditure while maintaining high average speeds is one of the most important determinants of successful race performance (Hausswirth and Lehénaff, 2001; Vercruyssen et al., 2002). For running and walking it is suggested that the performer spontaneously adopts the pattern of locomotion i.e. stride length-stride rate combination corresponding to the lowest energy cost (Brisswalter et al., 2000). Paradoxically, even though the most economical pedalling frequencies for stationary cycling lie between 50 and 80 rpm (Brisswalter et al., 2000; Chavarren and Calbet, 1999), road cyclists and triathletes typically prefer to use pedalling rates of 85-95 rpm during prolonged exercise at high intensities (Brisswalter et al., 2000; Lucía et al., 2001; Marsh et al., 2000a). A similar behaviour has been described in non-cyclists (Chavarren and Calbet, 1999). Such higher cadences may be selected to reduce the force per pedal stroke (Atkinson et al., 2003). This may act to either minimise recruitment of type II muscle fibres and optimise the use of the more efficient fatigue resistant type I fibres (Ahlquist et al., 1992), or to minimise the disruption of blood flow to the active muscle mass (Atkinson et al., 2003; Gotshall et al., 1996). The choice of a higher pedalling cadence has also been related to lower ratings of perceived exertion (Jameson and Ring, 2000), optimisation of the force-velocity relationship (Marsh et al., 2000b), minimal neuromuscular fatigue (Marsh et al., 2000a) and enhanced delta efficiency (Brisswalter et al., 2000; Chavarren and Calbet, 1999). Neptune and Hull (1999) observed that the neuromuscular quantities of individual muscle activation, force, and stress were minimised at a cadence of 90 rpm during sub-maximal (265 W) cycling. In support of this, Takaishi et al. (1996) demonstrated that the optimal pedalling rate estimated from neuromuscular fatigue in working muscles was not coincident with the cadence at which the smallest VO_2 was obtained, but with the preferred cadence of the cyclists (~90 rpm). However, none of these explanations provides a definitive answer to the question of why cyclists and non-cyclists select a pedalling frequency that is apparently less efficient (Chavarren and Calbet, 1999).

Bernard et al. (2003) investigated the effect of cycling cadence (60, 80, 100 rpm) on a subsequent running performance in triathletes (20 minutes cycling + 3000m run). There was no significant effect of cycling cadence on running performance, despite some changes in running strategies and metabolic contributions. However, the subjects were able to sustain a higher fraction of VO_{2max} during the 60 rpm run session – that is, 92% - than the 80 and 100 rpm run sessions – 84% and 87% of VO_{2max}, respectively. Bernard et al. (2003) therefore suggested that the contribution of the anaerobic pathway is more important after the higher pedalling rates (80 and 100 rpm) than after the 60 rpm ride and could lead during a prolonged running exercise to earlier experience of fatigue caused by metabolic acidosis. Gottschall and Palmer (2002) investigated the effect of cycling cadence (preferred cadence (PF), PF+20% and PF-20%) on subsequent running performance in triathletes (30 minutes cycling + 3200m run). After fast cadence cycling, run times averaged nearly a minute faster than after the slower cadence conditions. Stride frequency after the fast cadence condition was significantly higher than after the slower cadences. Stride length and leg angular displacements did not differ between conditions. These authors suggested that perseveration would cause individuals to unintentionally begin running with a stride frequency similar to the cadence of the previous cycling bout. Indeed, Gurfinkel et al. (1998) showed that when a suspended human leg is stimulated to produce a rhythmic stride pattern, the leg would continue to move at the prescribed frequency for numerous cycles, even after stimulation ceased. However, the effect of

Table 2. Physiological characteristics of the subjects obtained during a maximal cycling test. Values are expressed as mean (±SD).

Parameters	VO_{2max}	V_{Emax}	HR_{max}	VB(%VO_{2max})	P_{max}
	71.9 (5.1)	152.3 (22.2)	176 (12)	80.7 (7.0)	351.3 (15.5)

Abbreviations: VO_{2max} = maximum oxygen uptake (ml·kg^{-1}·min^{-1}); V_{Emax} = maximal ventilation, (litres·min^{-1}); HR_{max} = maximum heart rate (beats·min^{-1}); VB = ventilatory breakpoint; P_{max} = maximal power output (W).

perseveration on Olympic triathlon run performance is unknown. The studies described above have employed exercise protocols of short duration, which may fail to relate to actual race performances of longer duration (see Table 1). Indeed, both studies described above employ protocols that are significantly shorter than in a sprint triathlon (0.75km swim, 20km cycle, 5km run), which typically is the shortest triathlon distance in which competitions take place.

The effect of the cadence used in the cycle stage of Olympic distance triathlons on the subsequent run is unclear (Bentley et al., 2002). Typically, reducing the cadence at a given work rate causes an increase in force application to the pedals (Atkinson et al., 2003). This, in turn, may influence muscle recruitment patterns and fatigue responses during prolonged exercise (Lepers et al., 2001a). Therefore, it is possible that modifying the freely chosen cadence may affect subsequent running performance. No studies have examined the effects of cycling cadence on subsequent running performance for well-trained triathletes when using an exercise protocol of similar duration to Olympic triathlon (40km cycle, 10km run). Therefore, the main aim of this study was to examine the effects of different pedalling cadences on the performance of a subsequent 10km treadmill run. It is hypothesised that, compared with the preferred cadence, a fast cadence would increase stride frequency and subsequent 10km running performance. In contrast, a slow cycling cadence would decrease stride frequency, thereby decreasing subsequent 10km running performance. The null hypothesis is that there will be no effect of cycling cadence on subsequent 10km running performance. This study also aims to confirm the deterioration in running performance after a cycling event compared with an isolated run.

METHODS

Participants

Eight well-motivated recreational-standard male triathletes participated in this study. They had been training regularly and competing in triathlons for at least 2 years. For all subjects, triathlon was their primary activity. Weekly training distances were 4.9 ± 2.0 km for swimming, 188.8 ± 80.3 km for cycling, and 42.5 ± 12.5 km for running (mean ± SD). Age, body mass and stature of the participants were 38.9 ± 15.4 years, 72.2 ± 5.2 kg, and 176 ± 6 cm, respectively (mean ± SD). The participants were asked to abstain from exhaustive training throughout the experiment. Ethical clearance and medical and informed consent documents were completed prior to testing (BASES, 2000).

Maximal cycling test

All tests were conducted in a laboratory with an ambient temperature ranging from 19 to 23°C. On the first day of testing, participants performed an incremental maximal cycling test to determine maximal oxygen consumption (VO_{2max}), ventilatory breakpoint (VB), and maximal power output (P_{max}) (Table 2). The test was carried out on an adjustable Lode (Excalibur Sport) cycle ergometer. This session began with a warm-up at 100W for six minutes, after which power output was increased by 15W every 30 seconds until volitional exhaustion. Subjects were asked to maintain a pedalling cadence similar to what they would pedal at during competition. Oxygen consumption (VO_2), carbon dioxide production (VCO_2), ventilation (V_E), respiratory exchange ratio (RER), heart rate (HR), and pedalling cadence were recorded every 30 seconds. All subjects achieved primary VO_{2max} criteria – that is, a plateau in VO_2 despite an increase in power output (Howley et al., 1995). P_{max} was determined as the mean value of the last minute. Ventilatory breakpoint was estimated subjectively using the criterion of an increase in V_E/VO_2 with no concomitant increase in V_E/VCO_2.

Cycle-run performance sessions

Each athlete completed in random order, three cycle-run sessions (65 minutes cycling and 10km treadmill run) and one isolated treadmill run (10km). 65 minutes cycling is representative of 40km cycling stage duration data for age-group triathletes participating in a World Cup race (Bentley et al., 2002). All tests were performed 5-7 days apart. Before the cycle-run sessions, subjects performed a 10 minute warm-up at 33% P_{max}. During the cycling bout of the cycle-run sessions, subjects had to maintain one of three cadences corresponding to preferred cadence (PC), PC+15% (fast cadence) or PC-15% (slow cadence). PC corresponded to the

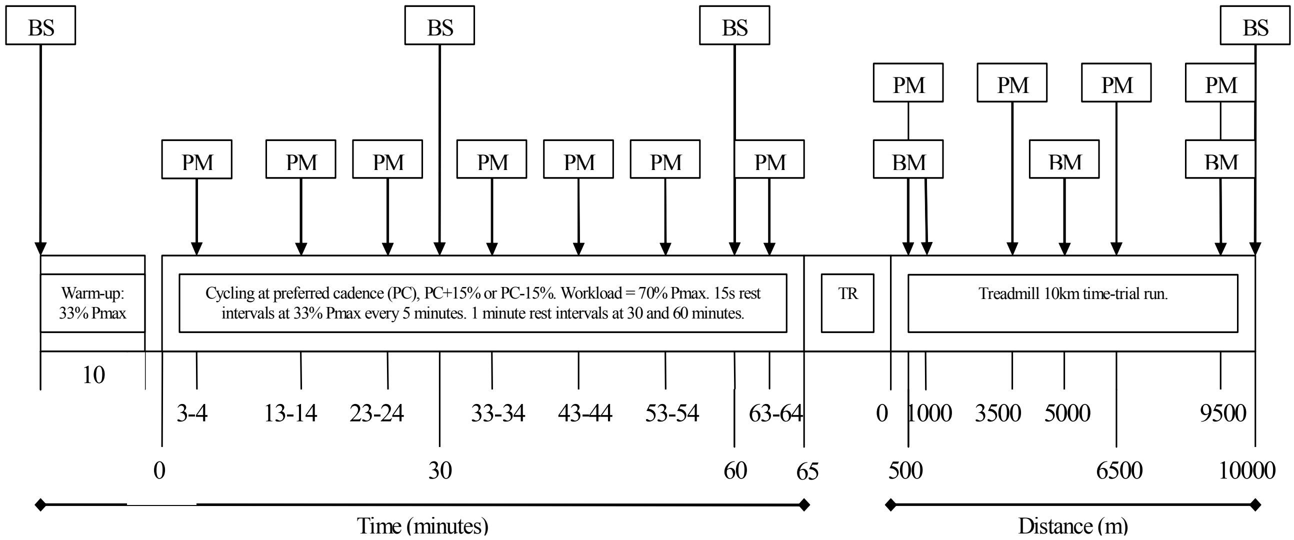

Figure 1. Representation of the 3 cycle-run sessions. TR, Cycle-run transition; BS, blood samples taken; PM, physiological measurements taken (V_E, VO_2, RER, HR, RPE); BM, biomechanical measurements taken (stride length, stride frequency, running velocity, and hip and knee angles at foot strike and toe-off).

pedalling cadence observed at 70% P_{max} during the incremental, maximal cycling test. Slow, preferred and fast cadences were 71.8 ± 3.0, 84.5 ± 3.6, and 97.3 ± 4.3 rpm, respectively (mean ± SD). These cadences are representative of the range of cadences selected by triathletes in competition (Bentley et al., 2002; Lepers et al., 2001a). Indeed, observations have shown that on a flat road at 40 $km{\cdot}hr^{-1}$ cadences ranged from 67 rpm with a 53:11 gear ratio (GR) to 103 rpm with a 53:17 GR. During an uphill climb at 20 $km{\cdot}hr^{-1}$, cadences ranged from 70 rpm with a 39:17 GR to 103 rpm with a 39:25 GR (Lepers et al., 2001a). Subjects cycled at an intensity corresponding to 70% P_{max} (~70-80% VO_{2max}) representative of Olympic distance simulation (Bernard et al., 2003). Cycling bouts were conducted on a Lode (Excalibur Sport) cycle ergometer which automatically adjusts resistance with cadence changes to maintain a particular power output. Cadence feedback was given continuously via a screen in front of the subjects. Each subject was instructed to maintain, as accurately as possible, the desired cadence. Rest periods of 15 seconds (at 33% P_{max}) were given at 5-minute intervals as well as two, 1-minute rest periods corresponding with blood samples at 30 and 60 minutes cycling (Figure 1). This accumulates to 5-minutes active recovery similar to the total freewheel duration data observed in an elite World Cup race (Bentley et al., 2002). Post-cycling, the subjects performed a self-paced 10km time-trial treadmill run on a 1% gradient, which most accurately reflects the energetic cost of outdoor running (Jones and Doust, 1996). Subjects were not aware of their running velocity. The treadmill had a maximum speed of 20 $km{\cdot}hr^{-1}$, which was sufficient to allow subjects to maintain their desired speeds. Subjects were appropriately familiarised with the treadmill prior to the cycle-run test days. Transition time between exercise modes was 39.3 ± 21.2 s (mean ± SD), which is similar to that observed by Millet and Vleck (2000) for elite triathletes in a World Championship competition. Subjects were allowed to ingest water *ad libitum*, during each testing session.

Measurement of physiological variables during the cycle-run sessions

VO_2, V_E, RER, HR and ratings of perceived exertion (RPE) (Borg, 1973) were recorded at 10-minute intervals from the 3rd minute during cycling and at 500m, 3500m, 6500m and 9500m during the run (Figure 1). Capillary blood samples were collected for blood lactate by finger prick using an Accu–Chek Softclix Pro blood sampler (Bodycare) into a micro cuvette (Sarstedt Ltd.) containing Potassium EDTA as a preservative. The whole blood was centrifuged (VWR Galaxy) to allow the plasma to be transferred into a Mira Analysis cup (ABX Diagnostics) via a Pasteur pipette (VWR). The samples were analysed using an automated ABX Mira lactate analyser (ABX Diagnostics). The following controls were used: ABX pentra N and P (ABX Diagnostics). Four blood samples were collected: at rest, 30 and 60 minutes cycling and post-10km run (Figure 1).

Measurement of biomechanical variables during the cycle-run sessions

During the running bouts a 25Hz video camera (Sony Handycam Vision DCR-100E) recorded the locations of markers placed on anatomical landmarks of each participant: head of the humerus,

Table 3. Physiological and biomechanical variables recorded during the run sessions. Data presented as mean (±SD).

Parameters	Isolated Run	Run After Cycling
FVO_{2max} (%)	80.0 (10.8)	78.3 (10.9)
HR (bpm)	167 (15)	162 (14)
RPE	14.2 (2.6)	14.9 (2.0) *
VE ($l.min^{-1}$)	110.8 (17.3)	108.3 (17.5)
RER	.92 (.05)	.88 (.05) *
Stride length (m)	2.51 (.31)	2.32 (.31)
Stride frequency (Hz)	1.48 (.08)	1.46 (.08) *
Hip angle foot-strike (°)	160 (4)	159 (3)
Hip angle toe-off (°)	189 (4)	186 (4) **
Knee angle foot-strike (°)	165 (4)	163 (4)
Knee angle toe-off (°)	163 (4)	160 (6) **
Running velocity ($km \cdot hr^{-1}$)	13.43 (1.67)	12.23 (1.77) *

Significantly (* $p < 0.05$, ** $p < 0.01$) different from the isolated run session.

greater trochanter of the femur, lateral condyle of the femur, and the lateral malleolus of the fibula. The camera was mounted with the lens perpendicular to the plane of motion. Kinematic data were recorded at 500m, 1000m, 5000m, and 9500m (Figure 1). Video data were captured (Pinnacle Studio 8) and edited (VirtualDub). Running velocity ($km \cdot hr^{-1}$) was recorded continuously using the treadmill display. Stride frequency (Hz) was determined as the inverse of the time to complete 1 complete stride. Stride length (m) was derived using the known stride frequency and running velocity values. Hip and knee angles at foot strike and toe-off were measured using printed digital images and a protractor.

Statistical analysis

All data are expressed as mean ± SD. A one-way repeated measures analysis of variance (ANOVA) was performed to measure the effects of cycling cadence upon 10km running time. A two-way repeated measures ANOVA (period time x cadence) was performed to analyse the effects of time and cadence using fraction of VO_{2max} (FVO_{2max}), V_E, RER, HR, RPE, blood lactate, running velocity, stride length, stride frequency, and hip and knee angles at foot-strike and toe-off as dependent variables. A *Bonferroni* post-hoc test was used to determine differences among all cycling cadences and times during exercise. $P < 0.05$ was set *a priori*.

RESULTS

10km performances

The performance of the isolated run was significantly faster than the run performed after cycling (44:45 ± 6:27 and 49:32 ± 7:57 $min \cdot s^{-1}$ for the isolated run and mean cycle-run sessions, respectively; $p = 0.001$). No significant effect of cycling cadence was observed on subsequent 10km running performance ($p = 0.801$, $\omega^2 = 0.006$). Running times were 49:58 ± 8:20, 49:09 ± 8:26, and 49:28 ± 8:09 $min \cdot s^{-1}$ for the slow, preferred, and fast rpm run sessions, respectively. Mean (±SD) values for physiological and biomechanical variables recorded during the isolated and post-cycling runs were presented in Table 3. RPE was significantly lower and RER, stride frequency, hip angle at toe-off, knee angle at toe-off, and running velocity significantly higher during the isolated run compared to the run performed after cycling ($p < 0.05$; Table 3). Conversely, there was no effect of prior exercise on FVO_{2max}, HR, V_E, stride length, hip angle at foot-strike, and knee angle at foot strike ($p > 0.05$; Table 3).

Cycling bouts of cycle-run sessions

Mean (±SD) values for physiological and biomechanical variables recorded during the cycling bouts of the cycle-run sessions were presented in Table 4. During the 65 minutes of the slow, preferred, and fast cycling bouts, average cadences were 71.8 ± 3, 84.5 ± 3.6, and 97.3 ± 4.3 rpm, respectively. Mean HR ($p = 0.012$; Figure 2) and V_E ($p = 0.026$; Figure 3) recorded during the fast cadence cycling bout were significantly higher than in the slow cadence condition. Conversely, there was no effect of cadence on FVO_{2max} ($p = 0.189$; Figure 4), blood lactate ($p = 0.265$), RER ($p = 0.585$) or RPE ($p = 0.087$). There was a significant effect of exercise time on FVO_{2max}, HR, RPE, V_E, and RER ($p < 0.001$).

Running bouts of the cycle-run sessions

Statistical analyses indicated a significant main effect of exercise time on FVO_{2max}, HR, RPE, V_E, stride length, stride frequency, hip angle at foot-strike, and running velocity ($p < 0.05$). HR in the preferred cadence run was significantly higher compared to the slow condition ($p = 0.025$; Figure 5). Running velocity was significantly lower at

Table 4. Physiological and biomechanical variables recorded during the cycle-run sessions. Data presented as mean (±SD).

Parameters	Cycle (72 rpm)	Run	Cycle (84 rpm)	Run	Cycle (97 rpm)	Run
FVO_{2max} (%)	74.0 (7.9)	76.8 (10.6)	77.7 (11.1)	79.5 (11.0)	78.7 (8.7)	78.5 (11.3)
HR (bpm)	152 (12)	158 (15)	157 (12)	168 (12) †	159 (11) *	160 (12)
Lactate ($mmol·l^{-1}$)	9.0 (3.2)	8.3 (3.2)	7.5 (3.8)	10.0 (3.3)	10.8 (4.9)	9.1 (4.0)
RPE	13.8 (1.6)	14.4 (1.7)	14.0 (1.5)	15.1 (2.0)	14.3 (1.4)	15.0 (2.2)
VE ($l·min^{-1}$)	978 (12)	107 (19)	103 (13)	111 (17)	111 (14) *	108 (17)
RER	.93 (.04)	.9 (.04)	.93 (.05)	.87 (.05)	.94 (.06)	.88 (.04)
Stride length (m)		2.29 (.3)		2.37 (.35)		2.32 (.3)
Stride frequency (Hz)		1.46 (.08)		1.45 (.07)		1.47 (.08)
Hip angle foot-strike (°)		159 (3)		159 (4)		159 (2)
Hip angle toe-off (°)		186 (6)		186 (4)		185 (4)
Knee angle foot-strike (°)		163 (3)		164 (4)		163 (4)
Knee angle toe-off (°)		159 (7)		160 (5)		160 (5)
Running velocity($km·hr^{-1}$)		12.02 (1.87)		12.38 (1.89)		12.28 (1.58)

* Significantly different from the slow and preferred cycle-run sessions: $p < 0.05$.
† Significantly different from the slow cycle-run session: $p= 0.025$.

500m following the slow cadence condition when compared to the other conditions ($p < 0.05$; Figure 6). V_E and RER were significantly higher at 9500m following the slow cadence condition compared to the other conditions ($p < 0.05$).

DISCUSSION

The main observations of this study confirm the negative effect of a cycling event on running performance when compared with an isolated run. There was also no significant effect of cycling cadence on subsequent 10km running performance ($p = 0.801$, $\omega^2 = 0.006$). Therefore, the null hypothesis was accepted. However, the results highlight an effect of cycling cadence on physiological responses (e.g. HR, V_E) and running patterns during the subsequent run.

Isolated run vs. runs performed after cycling

Previous studies (e.g. Bentley et al., 2002; Bernard et al., 2003; Hue et al., 1998) support the finding

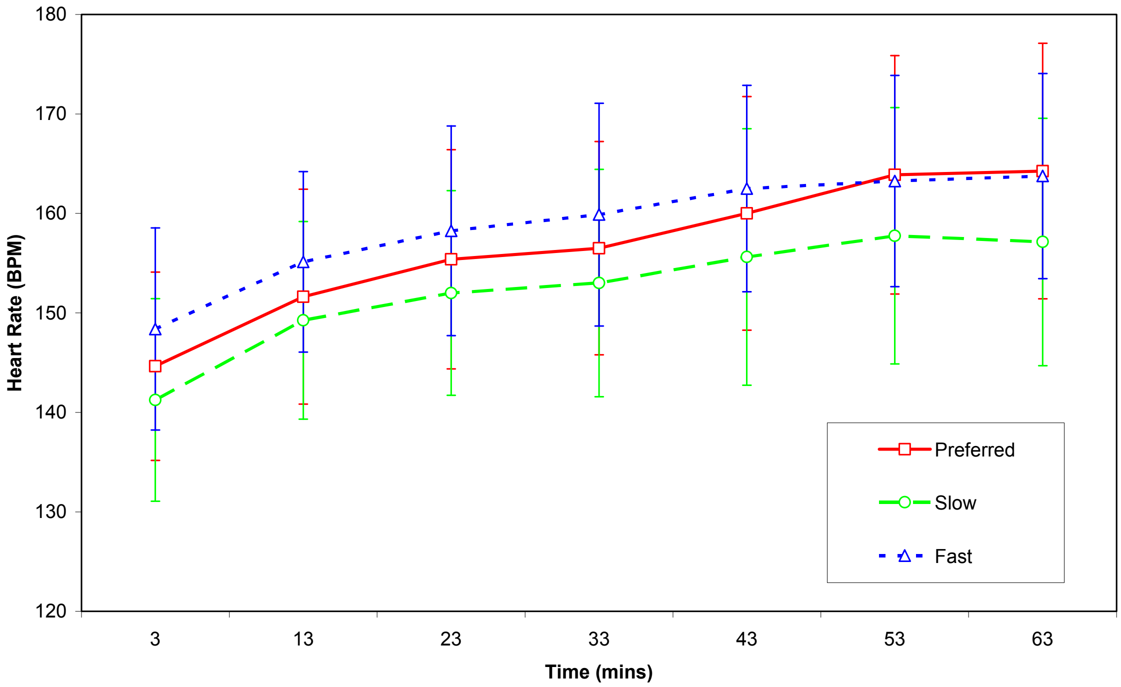

Figure 2. Mean heart rate at each cycling cadence during the cycling bouts of the cycle-run sessions (main effects of cadence and time: $p = 0.004$ and $p < 0.001$, respectively). HR was significantly higher at all times in the fast condition compared to the slow condition ($p \leq 0.025$).

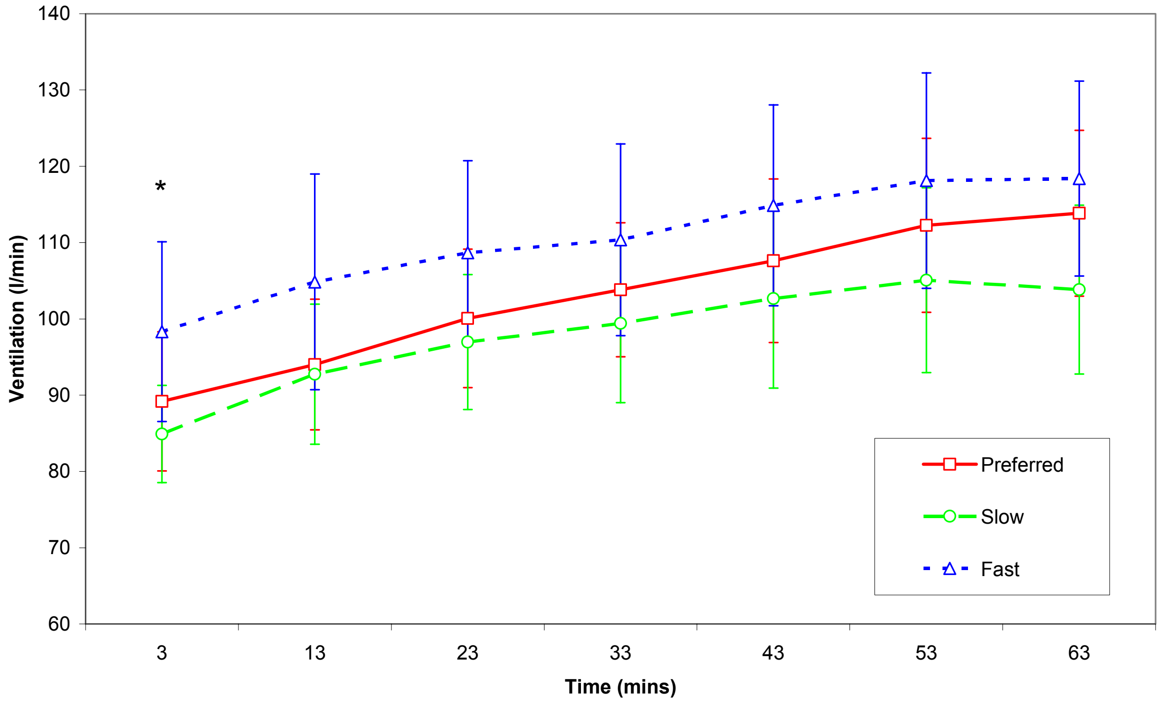

Figure 3. Mean V_E at each cycling cadence during the cycling bouts of the cycle-run sessions (main effects of cadence and time: $p = 0.026$ and $p < 0.001$, respectively). * Significantly higher V_E in the fast condition compared to slow and preferred conditions ($p < 0.05$).

that prior cycling has a negative affect on subsequent running performance. Bernard et al. (2003) observed, during a simulated triathlon event (20 minutes cycling, 3km run), a significant difference between 3km post-cycling run performance and isolated 3km run performance. The cycling event caused an increase in mean 3km race time (631 s) and a decrease in mean running velocity (17.2 km·hr^{-1}) compared with the isolated run (583 s and 18.5 km·hr^{-1}). Hue et al. (1998) also showed that a 10km run following 40km of cycling had higher oxygen cost than a 10km run alone performed at the same speed. In the present study, there was a significant increase in mean running time (49:32 min·s^{-1}) and a significant decrease in mean running velocity (12.2 km·hr^{-1}) compared with the performance in the isolated run (44:45 min·s^{-1} and 13.4 km.·hr^{-1}; $p = 0.001$). Therefore, a finding of the present study is that a prior cycling event can affect running performance over distances ranging from 3 to10 km.

The alteration in running performance after cycling could be related to the high metabolic load sustained by subjects at the end of cycling characterised by an increase in blood lactate concentration (7.45-10.76 mmol·l^{-1}) associated with a high percentage of VO_{2max} (77-83%) and HR_{max} (89-93%). These physiological changes may lead to cycling induced glycogen depletion, hyperthermia and dehydration (Hue et al., 1998; Lepers et al., 2001a) or alterations in stride length in the subsequent run, generally related to leg muscle fatigue (Gottschall and Palmer, 2002; Hue et al., 1998; Vercruyssen et al., 2002). However, recent reviews suggest that prior cycling does not significantly affect running biomechanics in well-trained triathletes (Bentley et al., 2002; Millet and Vleck, 2000). Conversely, in the present study, stride frequency ($p = 0.013$), hip angle at toe-off ($p = 0.004$), and knee angle at toe-off ($p = 0.004$) were all significantly higher during the isolated run compared to the run after cycling (Table 3). These changes may cause deteriorations in running economy; however, further research is required to determine how biomechanical variables measured during running are altered by prior cycling.

Cycling cadences and physiological and biomechanical characteristics of running

A classical view is that performance in triathlon running depends on the characteristics of the preceding cycling event, such as power output, pedalling cadence, and metabolic load (Bernard et al., 2003). However, the present study shows no effect of cycling cadences (~72-97 rpm) commonly used by triathletes on subsequent running performance ($p = 0.801$, $\omega^2 = 0.006$). Mean HR ($p = 0.012$; Figure 4) and V_E ($p = 0.026$; Figure 2) recorded during the fast cadence cycling bout were

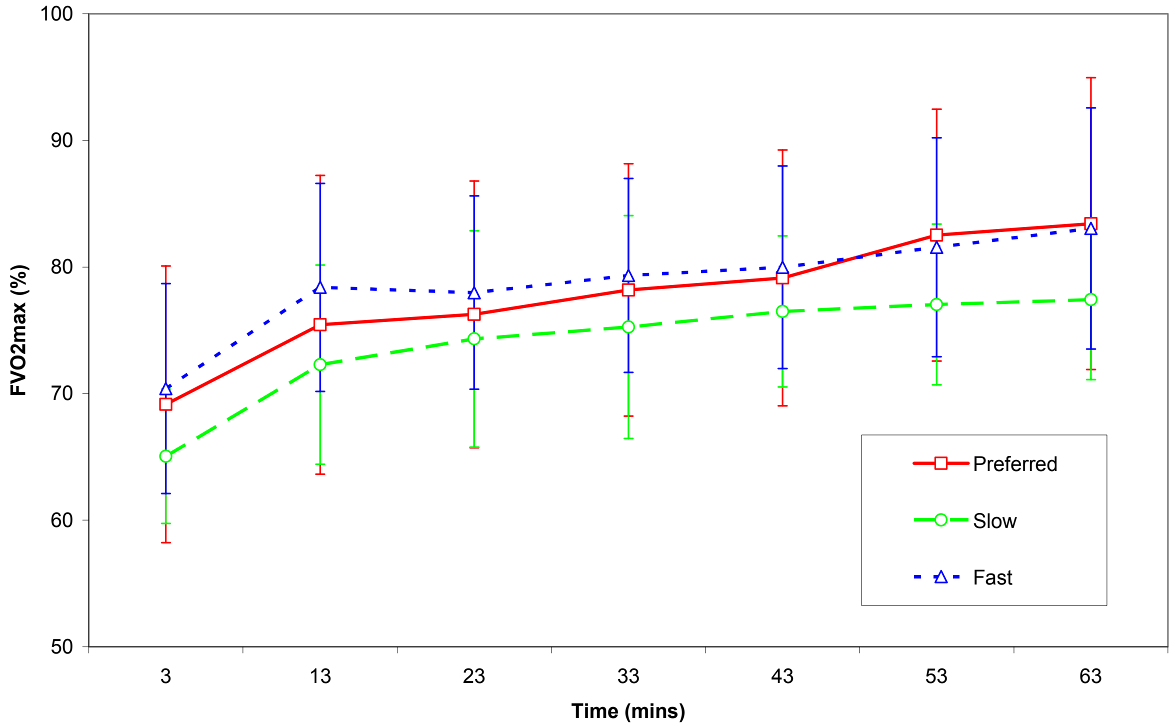

Figure 4. Mean FVO_{2max} at each cycling cadence during the cycling bouts of the cycle-run sessions (main effect of time, $p < 0.001$). There was no significant effect of cadence on FVO_{2max} ($p = 0.189$).

significantly higher than in the slow cadence cycling bout. The higher HR in the fast cadence condition is likely related to exercise-induced increases in circulating catecholamines, particularly norepinephrine (Deschenes et al., 2000), changes in central command, and feedback from the contracting muscles, particularly from mechanoreceptors (Gotshall et al., 1996). As a result, a combination of parasympathetic withdrawal and sympathetic activation would elevate HR in proportion to the increase in motor activity. Unfortunately, this can only be speculated as muscle activation patterns and circulating catecholamines were not measured. The higher V_E in the fast cadence cycling bout may be a result H^+ accumulation associated with the preferential recruitment of type II muscle fibres at higher pedalling cadences (Beelen and Sargeant, 1993). Conversely, there was no effect of cadence on FVO_{2max} ($p = 0.189$; fig. 4), blood lactate ($p = 0.265$), RER ($p = 0.585$) or RPE ($p = 0.087$) during the cycling bouts (Table 4). It may be that the extra energy expended to maintain higher HR and V_E values during fast cadence cycling was not sufficient to cause significant decrements in subsequent running performance. Although the cycling cadences used (72-97 rpm) are representative of the range of cadences selected by triathletes in competition (Bentley et al., 2002), they may also have not been sufficiently diverse to cause significant differences in subsequent running performance. Indeed, studies have demonstrated no significant effect of cycling cadence on neural and contractile properties of the knee extensor muscles when considering a range of 65-106 rpm (Lepers et al., 2001b; Sarre et al., 2003). Marsh et al. (2000a) have also demonstrated that cyclists can select a cadence within a range of 50-110 rpm without paying a substantial economy or efficiency penalty that might have a detrimental effect on performance. This data suggests that well-trained triathletes can easily adapt to the changes in cadence used habitually during racing, and that a minimisation of energy cost seems not to be a relevant parameter for the choice of cadence, at least in a non-fatigued state. These studies may help explain the non-significant effect of cycling cadence on 10km run times in the present study.

Despite the lack of cadence effect on 10km run time, the results indicate an effect of cycling cadence on subsequent running strategy, particularly the running velocity adopted at various points during the run. Running velocity was significantly lower at 500m following the slow cadence condition when compared to the other conditions ($p < 0.05$; Figure 6). Although final race times did not differ significantly, such a slower cycle-to-run transition may influence final race position. Indeed, Millet and Vleck (2000) reported that triathletes who remain up to 10% below their average 10km running speed over the first 500-1000m of the run, lose around 20 seconds. These observations suggest that immediately after the cycle stage, triathletes spontaneously choose a race strategy directly related to the pedalling cadence, but this seems to be transitory, as no significant differences between conditions were reported after the first 500m of running. This is in agreement with previous studies in which changes in stride pattern and running velocity were found to occur only during the first few minutes of the subsequent run (e.g. Hue et al., 1998; Vercruyssen et al., 2002). Perseveration has previously been described as a likely mechanism for the increased running velocity at the start of the runs performed after higher cadence cycling bouts (Gottschall and Palmer, 2002). Gottschall and Palmer (2002) suggest that it is possible that the neural firing rate after each cycling condition biases the firing rate used subsequently for running. For example, the high frequency firing rates during the fast cadence cycling bouts (~109 rpm) of their study appeared to have translated into an increased stride frequency during the subsequent 3200m running bouts. However, there were no differences in running stride frequency in the present study ($p = 0.115$), despite approaching significance at the 5% level. Unfortunately, the present study was limited by the use of a low frame rate (25 Hz) that will have reduced the accuracy of the stride frequency and stride length data obtained. Further research into the phenomena of perseveration and its' influence on triathlon running performance is needed. The fact that triathletes prefer to run at a faster pace after cycling at preferred and fast cadences seems to confirm different anecdotal reports of triathletes (Gottschall and Palmer, 2002). However, the significantly higher HR ($p = 0.025$, Figure 5) in the preferred run condition compared to the slow condition may be related to the subjects unintentionally exerting more effort because of their belief that this was their most economical cadence condition.

Many triathletes prefer to adopt a high pedalling cadence during the last few minutes of the cycle section of actual competition (Bernard et al., 2003). Three strategies may be evoked to characterise the choice of cycling cadence: speeding up in the last part of the cycle stage in order to get out quickly on the run (when elite triathletes compete in draft legal events); reducing power output and spin to minimise the effects of the bike-run transition; maintaining power output while increasing cadence. However, Bernard et al. (2003) previously showed that blood lactate values were significantly higher during a 100 rpm ride compared with two slower cadence conditions (60 and 80 rpm; ~275W work load). This suggests that it is not physiologically beneficial for the athlete to adopt high pedalling cadences in triathlon competition. However, the present study found no differences in FVO_{2max} ($p = 0.189$; Figure 3) and blood lactate ($p = 0.265$) between conditions. In any case, faster cadence cycling may have certain benefits that could counteract the potential increased energy cost of

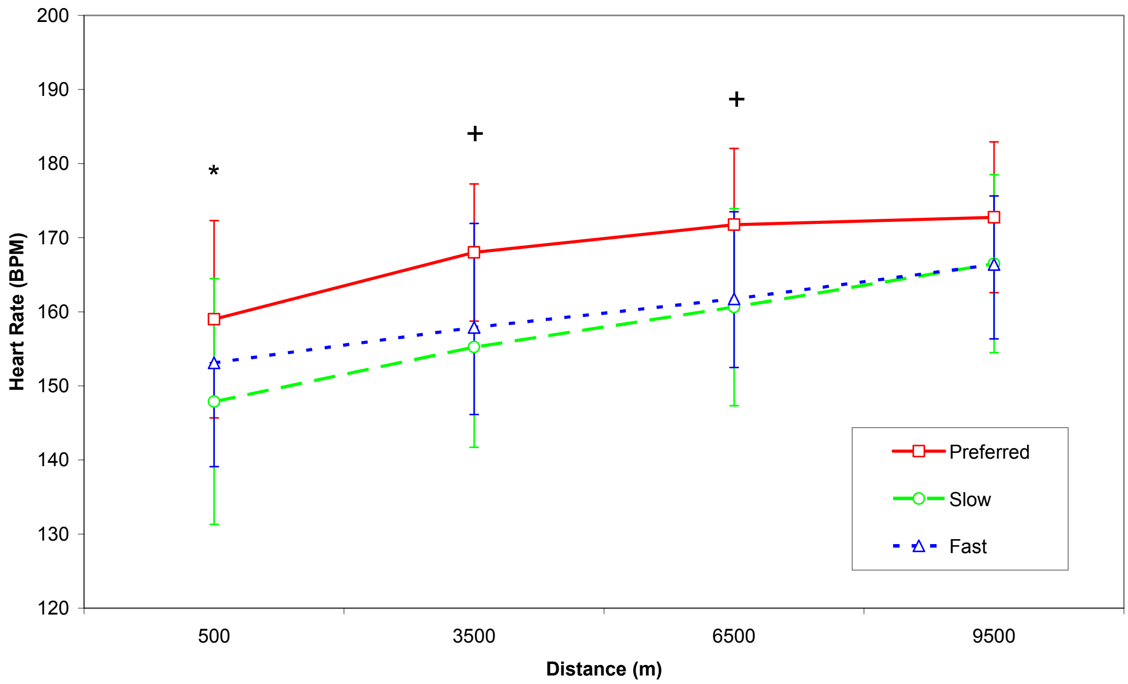

Figure 5. Mean heart rate during the running bouts of the cycle-run sessions (main effects of cadence and time: $p = 0.009$ and $p < 0.001$, respectively). * Significantly higher HR in the preferred condition compared to the slow condition ($p = 0.015$). + Significantly higher HR in the preferred condition compared to the slow and fast conditions ($p \leq 0.018$).

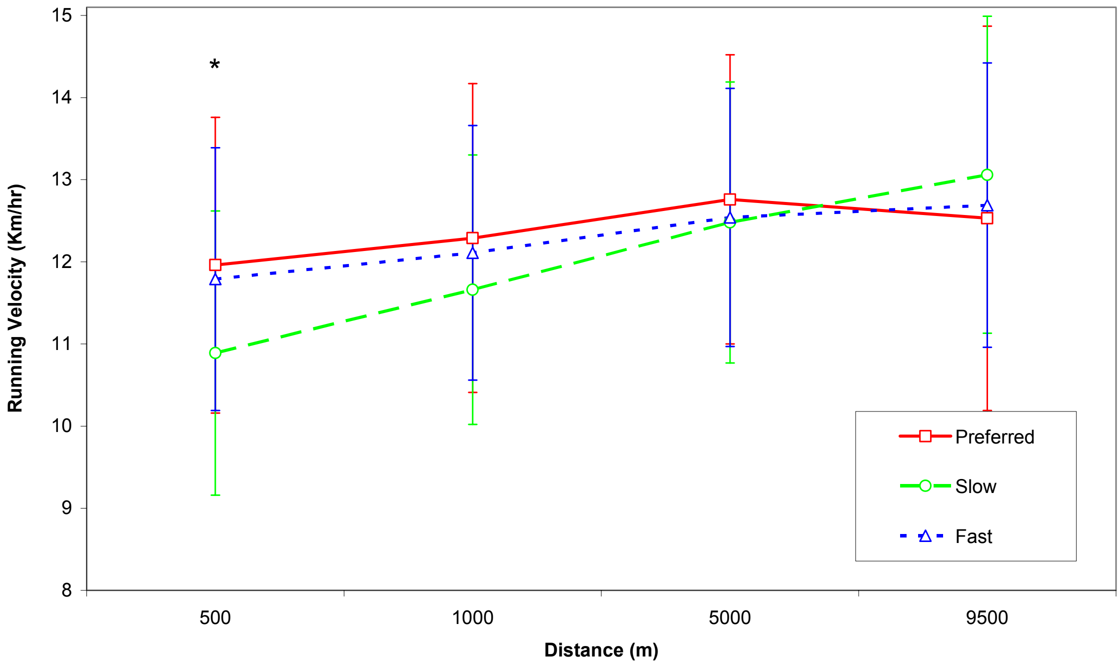

Figure 6. Mean running velocity (km·hr^{-1}) during the running bouts of the cycle-run sessions (main effect of time: $p < 0.05$). * Significantly lower running velocity in the slow condition compared to the preferred and fast conditions ($p < 0.05$).

such a strategy. For example, the action of the skeletal muscle pump is apparently improved in experienced male cyclists with increasing cadence from 70 to 110 rpm, resulting in elevation of muscle blood flow and cardiac output (Gotshall et al., 1996). A similar response has been observed in 11 year-old boys (Rowland and Lisowski, 2001). Takaishi et al. (1996) have also demonstrated that the optimal pedalling rate estimated from neuromuscular fatigue in working muscles was not coincident with the cadence at which the smallest VO_2 was obtained, but with the preferred cadence of the cyclists (~90 rpm). Whether or not these factors play a role in the selection of cycling cadence by triathletes is not known.

There appeared to be a gradual rise in oxygen uptake (VO_2 slow component) during cycling which seemed to be more prominent towards the end of the preferred and fast cadence cycling bouts compared to the slow cadence condition, where VO_2 appeared to have plateaued (Figure 3). Indeed, this may be a limitation in the present study as the validity of the measure of the energy cost of the cycling task from VO_2 values and the use of heart rate as an indicator of intensity level depends on the assumption that exercise was strictly aerobic (Brisswalter et al., 2000). Average blood lactate values during cycling of 7.45-10.76 mmol·l^{-1} suggest that this was not the case. The VO_2 slow component during the faster cadences may be associated with: enhanced recruitment of the less efficient type II fibres at higher movement frequencies; increased core and/ or muscle temperature; recruitment of additional muscles to stabilise the trunk; increased rates of pulmonary ventilation and cardiac output; lactate clearance or gluconeogenesis; and reduced blood flow to the active muscle mass (Pringle et al., 2003). However, support for the latter point appears equivocal (Gotshall et al., 1996; Rowland and Lisowski, 2001). Indeed, previous studies have confirmed the assumption of preferential recruitment of type II fibres at higher pedal rates (Beelen and Sargeant, 1993; Brisswalter et al., 2000). This might lead to an increase in H^+ accumulation, a reduction in muscle pH and greater rates of glycogen depletion, which may be detrimental to subsequent running performance (Pringle et al., 2003). Unfortunately, muscle pH and glycogen depletion were not measured in the present study. However, there were no differences in RER ($p = 0.585$; Table 4) between cadence conditions.

Vercruyssen et al. (2002) demonstrated that higher cycling cadences (81-90 rpm) contribute to an increase in energy cost during cycling and the appearance of a VO_2 slow component during subsequent running, whereas cycling at the energetically optimal cadence (~72 rpm) leads to a stability in energy cost of locomotion with exercise duration. Miura et al. (1997) have also demonstrated that a small increment of VO_2 during cycling in a simulated laboratory triathlon test was a good predictor of overall Olympic distance triathlon performance. It may that cycling cadence becomes a more important variable during longer duration events such as middle and long course triathlons; however, further research is required. The relationship between pedalling cadence, muscle fibre recruitment, and cycling economy is also not clearly identified (Vercruyssen et al., 2002). Therefore, it could be interesting in such studies to analyse simultaneously the cycling economy variability and the activity of the larger working muscle mass involved in cycling at different cadences during prolonged exercise.

CONCLUSIONS

In conclusion, the results confirm the deterioration in running performance after a cycling event compared with an isolated run. The principal aim of the investigation was to evaluate the impact of different pedalling rates commonly used in training and competition on subsequent running performance. No significant effect of cycling cadence was found on 10km running performance, despite some changes in running strategies and physiological responses (e.g. HR, V_E). Therefore, the choice of cadence within the usual range does not seem to influence the performance of a 10km run. However, it remains difficult to establish a preferential pedalling strategy, because the exercise intensity of a cycling stage in a triathlon may largely fluctuate compared with a steady-state exercise bout as used in the cycling bouts of the present study. Some limiting factors of this study include a small sample size (n = 8) and associated small effect size (ω^2 = 0.006). Additionally, subjects were well-trained amateur triathletes and, therefore, the data may not be applicable to professional triathletes. For multidisciplinary activities, such as triathlon and duathlon, further research on the relationship between cycling cadence and performance of the subsequent run is required. Exercise duration and muscle fibre type distribution are important factors, which warrant research. The results also reinforce the necessity for triathletes to practice multi-block training in order to simulate the physiological responses experienced by the cycle-run transition.

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KEY POINTS

- Compared with an isolated run, completion of a cycling event impairs the performance of a subsequent run independently of the pedalling cadence.
- The choice of cadence within triathletes' usual range does not seem to influence the performance of a 10km run.
- The results reinforce the necessity for triathletes to practice multi-block training in order to simulate the physiological responses experienced by the cycle-run transition.
- Further research into the effects of cycling cadence on subsequent running performance is required.

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